Chemical Geology 368 (2014) 76–84

Contents lists available at ScienceDirect

Chemical Geology

journal homepage: www.elsevier.com/locate/chemgeo

Water depth affecting thaumarchaeol production in Lake Qinghai, northeastern Qinghai–Tibetan plateau: Implications for paleo lake levels and paleoclimate

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ARTICLE INFO

Article history:
Received 30 September 2013
Received in revised form 14 January 2014
Accepted 15 January 2014
Available online 23 January 2014

Editor: David R. Hilton

Keywords:
Thaumarchaeol
$\delta^{13}C_{org}$
Lake level
Paleohydrology
Lake Qinghai
Qinghai–Tibetan Plateau

ABSTRACT

Archaeal glycerol dialkyl glycerol tetraethers (GDGTs) are increasingly popular and versatile tool for palaeolimnology studies, but their applications in paleohydrology are scarce, especially for thaumarchaeol which is specific for the newly proposed phylum Thaumarchaeota. After investigating our published GDGT data of Lake Qinghai, we found that both the concentration of thaumarchaeol and the relative abundance of thaumarchaeol to total archaeal GDGTs (%thaum) in core-top sediments increased significantly with increasing water depth ($R = 0.88$ and 0.95, respectively), with lower concentrations of 5 ± 5 ng/g in shallow areas (water depth < 5 m) and higher concentrations of 121 ± 65 ng/g in deep areas (water depth > 10 m). This is likely because that the producers of thaumarchaeol, Thaumarchaeota, prefer living in the relative deeper zone in lacustrine systems, where probably both competition of ammonium (the substrate) from other microbes and light intensity are low. Therefore, we proposed that thaumarchaeol was mainly produced *in situ* and changes in %thaum might reflect water-depth variations in this closed-basin lake. The application of %thaum as a water-depth indicator in a Holocene sediment sequence of core QH-2011 provided a high-resolution relative lake-level history of Lake Qinghai which resembles that inferred from the $\delta^{13}C_{org}$ value obtained in the same core. This supports the use of %thaum as an indicator of lake water depth in paleohydrology studies, especially for medium lakes. Moreover, the records of the two independent proxies in core QH-2011 confirmed a shallow Lake Qinghai in the early Holocene and a late-Holocene highstand, highlighting the importance of local temperature (and evaporation loss) in controlling effective moisture in the arid/semi-arid region.

1. Introduction

As one of the most abundant and ubiquitously occurring lipids on Earth, archaeal lipids are increasingly popular and versatile for palaeoclimate studies. Close examinations of the distributions have led to the discovery that archaeal lipids might be used as proxies for certain environmental parameters (reviewed in Schouten et al., 2013), such as sea and lake water temperature (Schouten et al., 2002; Powers et al., 2010), water salinity (Turich and Freeman, 2011; Wang et al., 2013), and the input of soil organic matter to marine environments (Hopmans et al., 2004). Thaumarchaeol (Fig. 1), previously called crenarchaeol (Sinninghe Damsté et al., 2002), is a unique archaeal glycerol dialkyl glycerol tetraether (GDGT) specifically from the newly proposed phylum Thaumarchaeota (Brochier-Armanet et al., 2008; Pitcher et al., 2010; Spang et al., 2010). It is widespread in lake water column (Sinninghe Damsté et al., 2009; Blaga et al., 2011; Schouten

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http://dx.doi.org/10.1016/j.chemgeo.2014.01.009

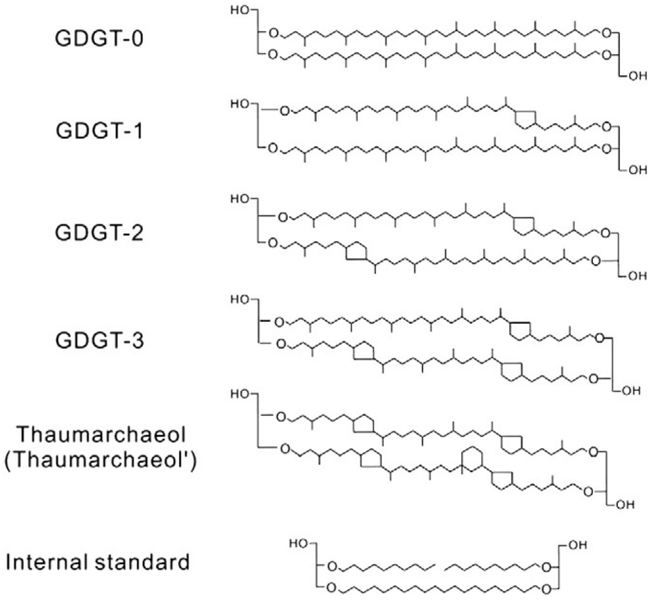

Fig. 1. Structures of archaeal lipids and internal standard discussed in the text.

et al., 2012; Woltering et al., 2012; Buckles et al., 2013) and modern and ancient lake sediments (Tierney and Russell, 2009; Bechtel et al., 2010; Powers et al., 2010; Tierney et al., 2010, 2012; Wang et al., 2012; Lu et al., 2013). Most previous investigations of thaumarchaeol in lakes focused on the application of it as a biomarker in microbial ecology studies, while little is explored on thaumarchaeol for the purpose of paleohydrology reconstructions (reviewed in Schouten et al., 2013). Interestingly, Tierney et al. (2010) recently reported that the concentration of thaumarchaeol is strongly correlated with lake depth in the core-top sediments from a large number of East African lakes. This observation inspired us to examine if paleo lake levels can be inferred by this ubiquitous archaeal lipid in lacustrine sediment cores.

The reconstruction of paleohydrologic history is essential for the understanding of climate variability, since it provides important palaeoclimate information such as changes in moisture balance or effective moisture (Street and Grove, 1976; Street, 1980; Fritz et al., 1991; Harrison et al., 1996; Newby et al., 2000; Verschuren et al., 2000; Zhang et al., 2004), and can also be used to predict future hydrological responses to climate change (Fritz, 1990). This is particularly true for closed-basin lakes, where changes in the balance between precipitation and evaporation result in fluctuations of both lake levels and the concentration of dissolved salts (Street-Perrott and Roberts, 1983; Fritz, 1990; Fritz et al., 1991). Lake Qinghai (Fig. 2), the largest saline lake of China which situated at the confluence of the East Asian monsoon, the Southwest monsoon and the westerly jet stream (Gao, 1962; An et al., 2000), is such a lake that is sensitive to global climate change on the northeastern Qinghai–Tibetan Plateau (Shi et al., 1958; Zhang et al., 1989; Ji et al., 2005; Shen et al., 2005; Liu et al., 2006, 2009; Henderson and Holmes, 2009; An et al., 2012). For this region therefore, the development of new proxies and the integration of multiple independent approaches for reconstructing reliable paleohydrologic history are of great importance.

The primary goal of the present study was to investigate the relationship between the relative abundance of thaumarchaeol to total archaeal GDGTs (%thaum) and water depth in modern and ancient Lake Qinghai sediments in order to assess the potential of %thaum as a paleohydrology proxy. For modern progress, the relationship between %thaum and *in situ* water depth was tested in the core-top sediments of Lake Qinghai based on our previously published data (Wang et al., 2012). As for ancient performance, the %thaum was compared with the $\delta^{13}C_{org}$ value in a Holocene sequence of core QH-2011, since the $\delta^{13}C_{org}$ value is indicative of variations in water depth (Liu et al., 2013) in this region. In addition, the Holocene paleohydrology history of Lake Qinghai was also discussed, based on the reconstructed relative lake-level history from core 1F (Liu et al., 2013) and QH-2011.

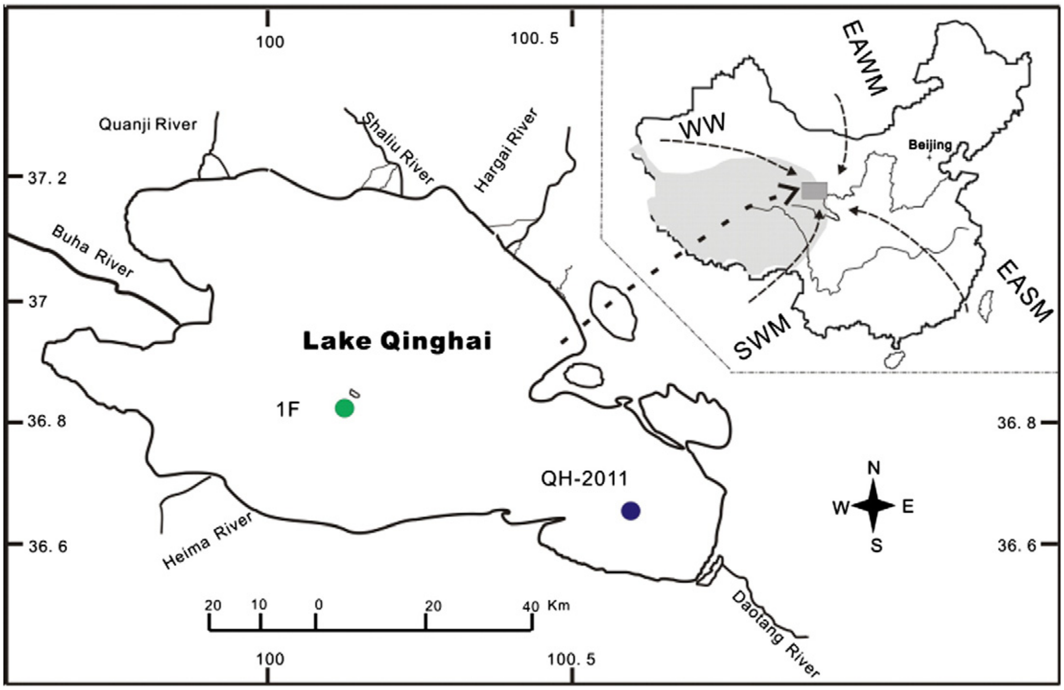

Fig. 2. The map of coring site (QH-2011) and atmospheric circulation patterns of this region. EASM, EAWM, WW and SWM are abbreviations for East Asian Summer Monsoon, East Asian Winter Monsoon, Westerly Wind, and Southwest Monsoon, respectively. Core 1F (An et al., 2012; Liu et al., 2013) in the southwestern sub-basin was also indicated.

2. Material and methods

2.1. Study site and samples

Lake Qinghai (36°32′ to 37°15′ N, 99°36′ to 100°47′ E) is an alkaline (pH: 8.8–9.3; Xu et al., 2010), brackish to saline (14–16 g/l) lake in Northwest China at an altitude of 3193–3194 m above sea level (a.s.l.). It lies in an intermountain basin and is now hydrologically closed with a lake area of 4260 km^2, a catchment area of 29,660 km^2, an average depth of 21 m, and a maximum depth of 27 m (Xiao et al., 2012). A cold and semi-arid continental climate prevails in the entire Lake Qinghai basin. Its annual mean temperature is ca. −0.7 °C and exhibits remarkably high seasonality, varying from ca. −11 °C in winter to ca. 12 °C in summer. Winds blow onshore at daytime and offshore at night with an average speed of 4–6 m/s (Colman et al., 2007). The mean annual precipitation is dominated by precipitation in June, July and August, which makes up about 65% of the total of 373 mm, showing a clear seasonality of monsoonal precipitation (An et al., 2012). However, its evaporation is 3–4 times higher than precipitation (Li et al., 2007). Presently, the annual input waters from direct rainfall and from runoff make nearly equal (~42%) contributions to Lake Qinghai, and the remaining approximately 16% of the water input is from groundwater seepage (Jin et al., 2010). Lake water residence time is about 33.4 years (Lister et al., 1991). The five largest rivers (Buha, Shaliu, Hargai, Quanji, and Heima Rivers; Fig. 2) account for 51.4, 16.1, 15.9, 3.6, and 0.7% of the total annual riverine inflow to the lake, respectively (Jin et al., 2010 and references therein). With a sparse population, the region experiences little effect of human activities (Xiao et al., 2012). Basic characteristics for the lake were summarized in Table 1.

In August 2011, a 580-cm long sediment core (QH-2011) was collected from the southeastern sub-basin of Lake Qinghai at a water depth ca. 24 m (Fig. 2; 36°39′34″ N, 100°35′37″ E). The core was immediately cut into 17 short segments (30–40 cm), stored on dry ice and transported to the Geomicrobiology Laboratory, China University of Geosciences, Beijing (CUGB). Thereafter, these sub-cores were cut into 2-cm slices in a clean room. Samples used for lipid analysis were then centrifuged to remove pore water and kept at −20 °C. The upper 4.35 m subsamples of the core, which covers approximately 12 ka, were used in this study.

2.2. Lipid analysis

Total lipids for 145 freeze-dried sediment samples were extracted ultrasonically using methanol (MeOH), MeOH/dichloromethane (DCM) (1:1, v/v), DCM, MeOH/DCM (1:1, v/v) and MeOH, respectively (Wang et al., 2012), after adding a known amount of C_{46} GDGT internal standard (IS, Huguet et al., 2006). The extracts were then dried under N_2, re-dissolved in hexane/isopropanol (99:1 v/v) and filtered. Archaeal lipids were analyzed by high-performance liquid chromatography/atmospheric pressure chemical ionization-mass spectrometry (HPLC/APCI-MS) on an Agilent 1200 HPLC connected to a QQQ 6460 MS as described in Zhang et al. (2012), a slightly modified method from Hopmans et al. (2000) and Schouten et al. (2007). An aliquot (5 μl) of each sample was injected and separation was achieved with an Alltech Prevail Cyano Column (150 mm × 2.1 mm, 3 μm). The elution gradient was: isocratic (5 min) at 99% hexane/1% isopropanol, followed by a linear gradient to 1.8% propanol in 45 min at a constant rate of 0.2 ml/min. Selected ion monitoring was used to target specific mass numbers including those for the IS (744), GDGT-0 (1302), GDGT-1 (1300), GDGT-2 (1298), GDGT-3 (1296), and thaumarchaeol and its isomer thaumarchaeol' (1292). Structures of these compounds are shown in Fig. 1. Quantification was performed by integration of the peak area of $[M+1]^+$ ions in the extracted ion chromatogram, and comparison to the C_{46} IS.

Table 1
Basic climate and hydrology data of Lake Qinghai.

Location	Lake Qinghai
Latitude, longitude	36°32′–37°15′ N, 99°36′–100°47′ E
Altitude	3193–3194 m a.s.l.
Climate	Cold and semi-arid continental climate
Lake water pH (Xu et al., 2010)	8.8–9.3
Lake water salinity	14–16 g/l
Lake area (Xiao et al., 2012)	4260 km^2
Catchment area (Jin et al., 2010)	29,660 km^2
Maximum water depth	~27 m
Average water depth	~21 m
Mean annual precipitation (An et al., 2012)	373 mm
Evaporation/precipitation ratio (Li et al., 2007)	3–4
Lake water residence time (Lister et al., 1991)	~33.4 years
Annual mean temperature (Colman et al., 2007)	−0.7 °C

The %thaum was calculated as follows:

$$\%\text{thaum} = \text{thaum}/(\text{GDGT}-0+\text{GDGT}-1+\text{GDGT}-2+\text{GDGT}-3+\text{thaum}+\text{thaum}').$$

2.3. Carbon isotope analysis

Totaling 114 samples were analyzed for total organic carbon isotope following Liu and Xing (2012). Briefly, the freeze-dried samples were ground in an agate mortar, sieved through a 100 mesh screen and homogenized. Approximately 1–2 g of the sieved sediment sample was treated with 2 M HCl for 24 h at room temperature to remove carbonates. Subsequently, the samples were rinsed to a pH of ~7 with distilled water and dried at 40 °C. The dried samples were combusted for 4 h at 850 °C in evacuated sealed quartz tubes in the presence of 1 g CuO, 1 g Cu and a Pt wire. The carbon dioxide was then cryogenically purified. The isotopic ratios of the purified CO_2 were measured using a Finnigan MAT 251 gas source mass spectrometer at the Institute of Earth Environmental, Chinese Academy of Sciences (IEECAS). The overall precision was less than 0.2‰.

3. Results

3.1. Age model for core QH-2011

Six AMS radiocarbon dates on total organic carbon of bulk sediments were measured for core QH-2011 (Table 2). As is shown in Fig. 3a, our ^{14}C age–depth relationship is consistent with those of other cores taken from the southeastern sub-basin of Lake Qinghai (Zhang et al., 1989; Shen et al., 2005; Wang et al., 2011). Shen et al. (2005) concluded that the reservoir effect could be 1039 years based on the regression line between depth and 8 ^{14}C dates. Wang et al. (2011) then reported that the ^{14}C ages for land-derived lignin (generally not affected by reservoir effect of lakes) were 728 years and 1222 years younger than the corresponding ^{14}C ages for two separate layers. Therefore on average, the reservoir effect was tentatively attributed to be 996 years for core QH-2011 here. The reservoir-corrected ^{14}C ages were converted to calendar year using the IntCal13 calibration curve (Reimer et al., 2013), and consolidated with those for core QH-2005 (Wang et al., 2011), which was retrieved from a similar site at a water depth of 24 m in the southeastern sub-basin, to build the chronology for core QH-2011 as follows: for depth 0–315 cm, age (cal BP) = 22.43 × depth (cm); for depth 316–579 cm, age (cal BP) = 40.68 × depth (cm) − 5762 (Fig. 3b).

3.2. Lipid and $\delta^{13}C_{org}$ records for core QH-2011

The %thaum for the upper 4.35 m of core QH-2011varied between 0.6 and 63.6%, showing an increasing trend from early Holocene to late Holocene (Fig. 4a). Thaumarchaeol was most abundant at

Table 2
AMS ^{14}C and calendar age of core QH-2011.

Sample ID	Depth (cm)	Conventional ^{14}C age (a. BP)	Reservoir age (a. BP)	Reservoir-corrected ^{14}C age (a. BP)	Calendar age (a. BP)
QH11-1D-4-34	576	15,770	996	14,774	17,969
QH11-1D-2-18	488	12,530	996	11,534	13,373
QH11-1C-1-12	352	7300	996	6304	7220
QH-1B-2-20	222	4540	996	3544	3828
QH11-1A-4-18	116	4050	996	3054	3281
QH11-1A-2-24	58	3020	996	2024	1972

4.8 ka BP. The $\delta^{13}C_{org}$ values ranged from −18.6 to −30.4‰, and generally decreased towards present (the top of the core). The most negative and positive $\delta^{13}C_{org}$ values occurred at 4.3 ka BP and 10.7 ka BP, respectively (Fig. 4b). Remarkably, oscillations of the two records corresponded well with each other from 5 to 12 ka BP.

Briefly, we divide our Holocene records into three intervals (late Holocene: 0–4 ka BP; mid Holocene: 4–8 ka BP; early Holocene: 8–12 ka BP). The %thaum averaged 50.3, 28.7 and 8.7% respectively, the average values of $\delta^{13}C_{org}$ were −26.4, −24.5 and −22.3‰ respectively, for the three Holocene intervals. Overall, our results display that the values of $\delta^{13}C_{org}$ were much higher in the early Holocene compared with those for late Holocene, while it is opposite for the %thaum values (Fig. 4).

4. Discussion

4.1. Relationships between concentration of thaumarchaeol and lake water depth in core-top sediments

Thaumarchaeol was more abundant in deep areas with water depth > 10 m (averaging 121 ± 65 ng/g) than in shallow areas with water depth < 5 m (averaging 5 ± 5 ng/g) for the core-top sediments of Lake Qinghai (Wang et al., 2012). Consequently, the concentration of thaumarchaeol in these sediments increased significantly with increasing water depth (Fig. 5a; $R = 0.88$, $p < 0.01$). This hold truth as well when concentrations of thaumarchaeol were normalized against total archaeal GDGTs, as %thaum also correlated significantly with water depth (Fig. 5b; $R = 0.95$, $p < 0.01$). Actually, Tierney et al. (2010) have already observed a positive relationship ($R = 0.73$; $p < 0.01$) between the concentration of thaumarchaeol in core-top sediments and water depth for lakes in East Africa including small maar crater lakes, large tectonic lakes, valley swamps, and high-elevation mountain lakes. Their dataset covers a wide range in elevation, salinity, depth, water temperature, water pH, surface area, catchment area, and sedimentary organic carbon content, while water depth is the only environmental variable that was shown to be significantly correlated with thaumarchaeol concentration across the full gradient of African lake environments (Table A3 in Tierney et al., 2010). The positive relationship between the concentration of thaumarchaeol and *in situ* water depth for core-top sediments in a single lake (Lake Qinghai; this study), together with that for a diverse set of lake groups (East African lakes; Tierney et al., 2010), suggest that water depth is a significant factor determining the concentration of thaumarchaeol in core-top sediments in lacustrine system.

A preference of Thaumarchaeota for a niche in the oxycline/thermocline and nitrocline of the water column of lakes has been observed in some recent studies (Pouliot et al., 2009; Llirós et al., 2010; Blaga et al., 2011; Auguet et al., 2012; Schouten et al., 2012; Woltering et al., 2012; Buckles et al., 2013). Specifically at two sites for Lake Qinghai, applying DNA based molecular approach, Jiang et al. (2009) has shown that archaeal *amoA* genes were most abundant at about 5 m throughout the water column, among the investigated depths (0 m, 5 m, 10 m, 13 m, and 20 m or 23 m). Therefore, the producers of thaumarchaeol, Thaumarchaeota, may preferably live in the relative deeper zone in lacustrine systems. This might account for the positive relationship between water depth and the concentration of thaumarchaeol in surface lacustrine sediments. The preference of Thaumarchaeota for a niche in the relative deeper zone in lake water can be further viewed from two aspects. First, since all cultivated Thaumarchaeota are nitrifiers (e.g. Könneke et al., 2005; De la Torre et al., 2008), they might depend on the release of ammonia derived from descending particulate organic matter of phytoplanktonic origin for the energy source in lakes (Schouten et al., 2013). However, the ammonia in the photic zone will be recycled primarily by more efficient photoautotrophs or heterotrophs. Therefore, the more slowly growing chemoautotrophic Thaumarchaeota occur predominantly below the upper zone, where competition of ammonia from other microbes is low (Tierney et al., 2010; Schouten et al., 2013 and references therein), due to their ability to thrive in environments with low oxygen and ammonia concentrations (Erguder et al., 2009; Buckles et al., 2013). This is supported by the finding in Lake

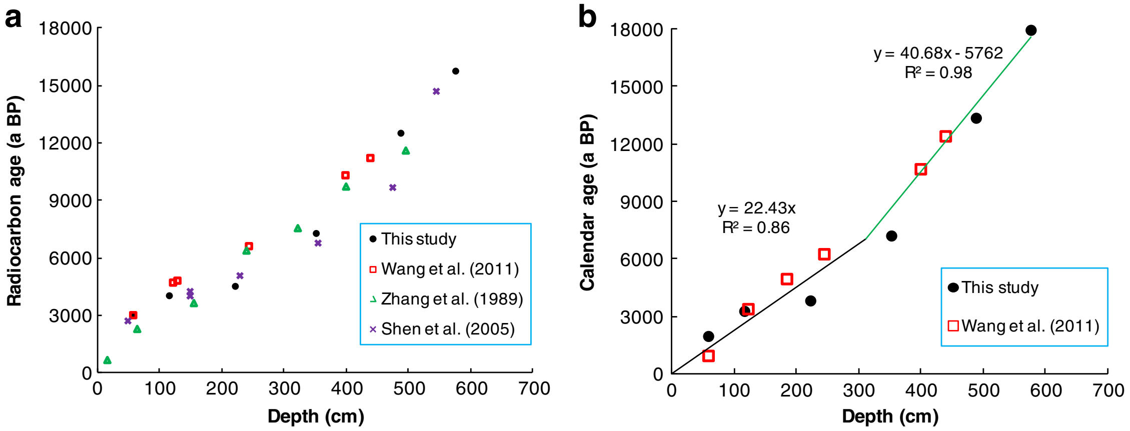

Fig. 3. Age–depth relationships for core QH-2011: (a) comparison of radiocarbon ages of this study with cores QH85-16A (Zhang et al., 1989), QH-2000 (Shen et al., 2005) and QH-2005 (Wang et al., 2011) taken from the southeastern sub-basin of Lake Qinghai; (b) the chronology for core QH-2011, based on converted age of this core and core QH-2005 (Wang et al., 2011). Two regression lines were built for the first 8 ages and last 4 ages, respectively. They cross at 315–316 cm.

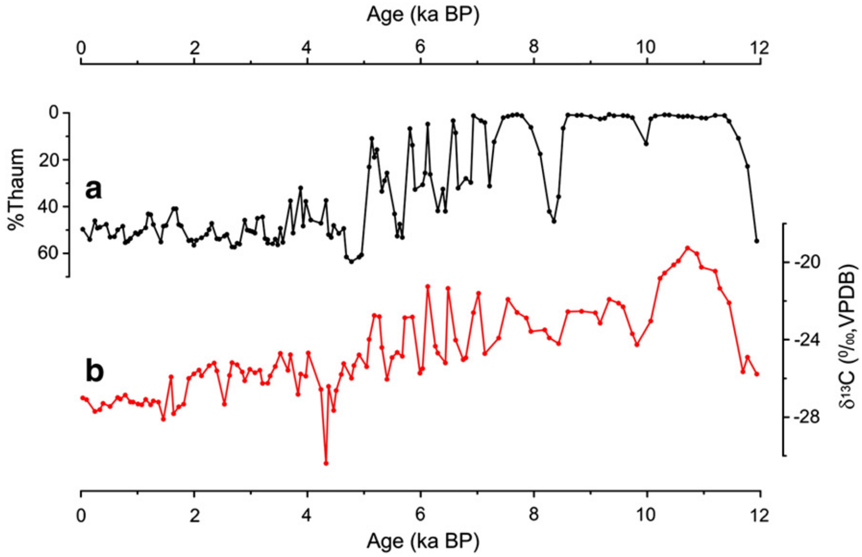

Fig. 4. Fluctuations of Holocene (a) %thaum record and (b) $\delta^{13}C_{org}$ record for core QH-2011.

Superior that both thaumarchaeol and archaeal (predominantly Thaumarchaeotal) 16S rRNA genes were most abundant below the depth of the chlorophyll maximum during the thermally stratified period (Woltering et al., 2012). In addition, some Thaumarchaeota are reported to be suppressed by a high light level (Merbt et al., 2012 and references therein), which consequently might also prohibit them from thriving right near the surface layer of lake water (Schouten et al., 2013). Taking into account both of the two aspects, the size of the thaumarchaeol production zone might increase with water depth, and therefore, the concentration of thaumarchaeol and %thaum in core-top sediments correlates positively with water depth.

4.2. Potential and limitations of %thaum as a paleohydrology proxy

The positive correlations of water depth with both the concentration of thaumarchaeol and %thaum in the core-top sediments imply that thaumarchaeol might be potentially used for reconstructing past lake water depth in lacustrine sediment cores. However, compared with the concentration of thaumarchaeol, %thaum is a ratio that is less dependent on lipid quantification, sedimentation rate and potential diagenesis. Additionally, the correlation between %thaum and water depth is more significant than that between thaumarchaeol concentration and water depth in our dataset (Fig. 5). Therefore, we tentatively suggest using %thaum as an indicator of paleo water-depth variations for Lake Qinghai.

Several issues should be addressed before applying %thaum as a paleo lake-level indicator. Firstly, we note that the relationship between %thaum in core-top sediments and lake water depth exhibited some scatters for Lake Qinghai. This is possibly due to that other factors, in addition to water depth, might also affect %thaum for different sites. For example, it is possible that without change of lake depth, the change of oxygen concentrations also changes the %thaum. However, these effects might be relatively smaller for a specific core site during the evolution of a lake, given the consistency of the %thaum record with the $\delta^{13}C_{org}$ lake-level record in core QH-2011 (discussed below). Secondly, it could be argued that if thaumarchaeol was mainly produced *in situ* in the lake. The significant positive water depth-%thaum relationship in the core-top sediments might indicate that the influence of soil-derived thaumarchaeol is generally insignificant, at least for the application of it as an indicator of *in situ* water depth in palaeoclimatic reconstructions. Moreover, the diagenesis effect over geological time scales might also bias the downcore %thaum record. However, it has been reported that oxygen exposure time of ~1000 years does not have a large effect on TEX_{86} values (Schouten et al., 2004), suggesting that selective degradation might be insignificant for archaeal lipids on millennial scale, since they are similar in chemical structures. Therefore, for

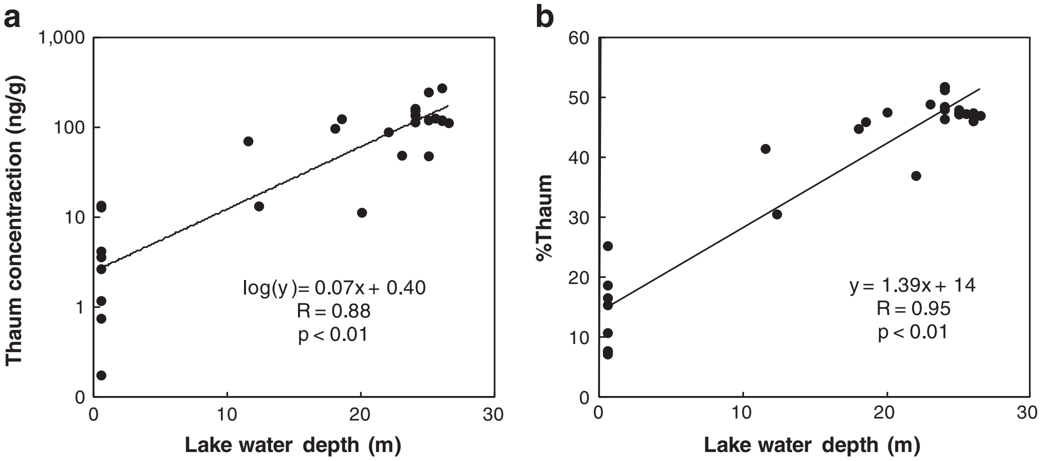

Fig. 5. Correlations of water depth with (a) thaumarchaeol concentration and (b) %thaum for the core-top sediments of Lake Qinghai. Data from Wang et al. (2012).

downcore sediments that are generally oxygen-depleted, degradation processes should be even much weaker, at least for the Holocene period. Considering all these discussed above, we suggest that %thaum might be reliable for qualitatively reconstructing paleohydrology changes of Lake Qinghai presently. Further investigations and examinations are still required to determine whether this proxy is widely applicable for other lacustrine systems.

4.3. %Thaum-inferred Holocene lake-level history of Lake Qinghai

The %thaum was tentatively applied as a lake-level proxy on core QH-2011, which was recovered from the center of the southeastern sub-basin of Lake Qinghai, to generate the Holocene lake-level history inferred from archaeal lipids. Based on the modern %thaum–depth relationship for Lake Qinghai, the %thaum record indicates that the lake was generally shallow in the early Holocene (<5 m), with two periods of relatively higher lake levels being at the beginning and the end of this period, respectively. After the early-Holocene lowstand, Lake Qinghai increased from a shallow lake to its maximum at ~4.8 ka BP with 6 millennial-scale oscillations superimposing on the expansion, as suggested by variations in %thaum values (Fig. 6a). Afterwards, even though an obvious decline in lake level occurred, the decreased lake level at that time was still higher compared with most other periods in the early and mid Holocene. Finally, Lake Qinghai was persistently at its highstand since ~4 ka BP, despite that the %thaum record still reveals some lake-level fluctuations in the context of a highstand (Fig. 6a).

In order to further examine the %thaum as a lake-level proxy, the $\delta^{13}C_{org}$ value of core QH-2011was also analyzed for comparison (Fig. 6b). The $\delta^{13}C_{org}$ value was newly suggested indicative of variation in water depth of Lake Qinghai and its satellite lakes, because that coretop sediment $\delta^{13}C_{org}$ become more negative with increasing water depth, predominantly due to the shift of aquatic plant types with water depth (Liu et al., 2013). When putting the Holocene %thaum record and the $\delta^{13}C_{org}$ record of core QH-2011 together, it is clear that the two proxies fit well with each other, both in trend and fluctuations, especially for the early and mid Holocene episodes (Fig. 6a,b). Relatively lower %thaum values generally corresponded to more positive $\delta^{13}C_{org}$ values (thus lower lake levels), and vice versa. The consistency of %thaum record with $\delta^{13}C_{org}$ record in the same core of Lake Qinghai strongly supports the applicability of %thaum as a proxy for evaluating past lake water depth.

4.4. Implications for paleoclimate of Lake Qinghai

Despite that lake-level variations of Lake Qinghai have been investigated extensively on the basis of radiocarbon dating or optically stimulated luminescence (OSL) dating of remnant paleo shoreline features (e.g. Chen et al., 1990, 1991; Yuan et al., 1990; Lister et al., 1991; Wang and Shi, 1992; Zhang et al., 1994; Rhode et al., 2010; Liu et al., 2011), there are only a few continuous records of lake-level changes covering the Holocene (Yu, 2005; Liu et al., 2013). The %thaum and the $\delta^{13}C_{org}$ records in core QH-2011 (Fig. 6a,b; this study), in combination with the $\delta^{13}C_{org}$ record in core 1F in the center of the southwestern sub-basin (Fig. 6c; Liu et al., 2013), uniformly suggest a three-stage evolution history of Holocene lake levels for Lake Qinghai.

(1) A generally stable early-Holocene shallow lake. The %thaum was lowest while the $\delta^{13}C_{org}$ values were most positive in the early Holocene, suggesting that Lake Qinghai might be very shallow during this period (Fig. 6). The inferred lower lake level in the early Holocene is evidently supported by the occurrence of various amount of *Ruppia maritima* seeds in the early-Holocene sediments (Yu, 2005; Liu et al., 2013), since *Ruppia* prefers living in shallow water (0.5–2 m, not more than 4 m) in fresh to brackish lakes (Verhoeven, 1979; Yu, 2005).

(2) A mid-Holocene expanding lake with fluctuating lake levels. From 8 to 4 ka BP, all the 3 records suggest that the water depth of Lake Qinghai increased from <5 m to ~20 m, with several obvious millennial-scale oscillations superimposing on the expansion, especially when looking at the original data not filtered by 3-point moving (Fig. 6). The large variations of both %thaum and $\delta^{13}C_{org}$ during this period may also indicate that the two proxies are particularly sensitive in reconstructing lake-level

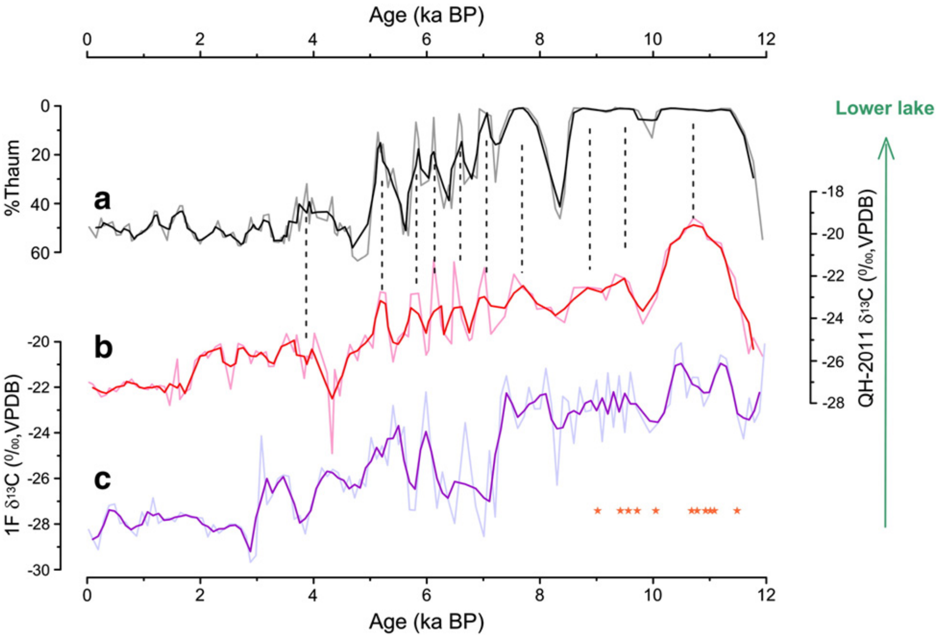

Fig. 6. The Holocene paleohydrology history of Lake Qinghai inferred from different proxies. (a) The %thaum record of core QH-2011. (b) The $\delta^{13}C_{org}$ record of core QH-2011. (c) The $\delta^{13}C_{org}$ record of core 1F (Liu et al., 2013). The thick lines in each figure are the 3-point moving average. The dashed lines indicate relatively more positive $\delta^{13}C_{org}$ values and lower %thaum for core QH-2011, which consistently imply relatively lower lake levels. Yellow five-pointed stars in c denote the age of core 1F at which the seeds of *Ruppia* occurred (Liu et al., 2013).

variations when the lake varied between shallow and deeper ones.

(3) A late-Holocene highstand. Lake Qinghai was relatively large and stable in the late Holocene, since the %thaum was persistently higher while the $\delta^{13}C_{org}$ values were persistently more negative during this period. The late-Holocene highstand stage is in agreement with Lu et al. (2011), who observed that sand deposits mainly occurred during early Holocene, while loess and paleosol deposits were most abundant in the late Holocene, based on 24 OSL age determinations along with multi-proxy data for Eolian deposits around the lake.

The reconstructed Holocene lake-level history of Lake Qinghai may provide insight into how moisture balance responds to regional and global climate change in this critical region. At first glance, our reconstructed lake-level history of Lake Qinghai seems difficult to be explained by the widely held conceptual model concerning the evolution of summer monsoon. According to this model, the insolation-forced summer monsoon which transports moisture to this region should have intensified in the early Holocene and weakened towards the late Holocene (Berger and Loutre, 1991; Ji et al., 2005; An et al., 2012), and therefore, the precipitation should be higher in the early Holocene. However, it is important to note that the solar radiation would also substantially affect the surface temperature and thus evaporation loss, and enhanced evaporation induced by elevated temperature might have exceeded the enhanced precipitation brought by intensified summer monsoon in this arid/semi-arid region (Lu et al., 2011; Liu et al., 2013). Therefore, the three-stage evolution history of Holocene lake levels for Lake Qinghai possibly reflects that local temperature and evaporation is very important in controlling effective moisture in this region. In fact, we also observed a peak of higher lake level at ~8.4 ka BP for Lake Qinghai (Fig. 6a,b), which might correspond to the 8.2-ka BP cold event, within dating uncertainties. This suggests that a decrease of temperature may have indeed increased the effective moisture here. Moreover, enhanced winter precipitation (induced by low temperature) might also partially account for the increased effective moisture in the late Holocene. However, the hypothesis of enhanced late-Holocene snowfall requires further evidences coming from winter precipitation reconstructions in Lake Qinghai region.

5. Conclusions

The concentration of thaumarchaeol or the relative abundance (%thaum) significantly correlated with *in situ* lake water depth in the core-top sediments of Lake Qinghai. As a mechanism, this is possibly because that the producers of thaumarchaeol, Thaumarchaeota, prefer living in the relative deeper zone in lacustrine systems, where competition of ammonium (the substrate) from other microbes and light intensity are both low. Therefore, we proposed that %thaum can potentially yield continuous and high-resolution reconstructions of relative lake-level changes in this closed-basin lake and applied it on the upper 4.35-m of core QH-2011 to generate a %thaum-inferred Holocene lake-level history. Based on the %thaum record, the lake was shallow in the early Holocene, followed by an expansion with millennial-scale oscillations during the mid Holocene. Afterwards, it remained deep in the Late Holocene with fluctuating water depth. Further analyses of the $\delta^{13}C_{org}$ value in the same core showed that the %thaum-inferred lake-level history coincided well with that inferred from the $\delta^{13}C_{org}$ value. These confirm that %thaum is a useful addition to the indices presently available for tracing lake-level variations in paleohydrology studies, although more investigations and examinations are still required in order to determine whether this proxy is widely applicable.

The reconstructed lake-level history for the southeastern sub-basin in this work is consistent with the $\delta^{13}C_{org}$-inferred lake-level history of Lake Qinghai in the southwestern sub-basin (Liu et al., 2013), within dating uncertainties. The two studies uniformly suggest a three-stage evolution history of Holocene lake levels for Lake Qinghai, which appears to be in conflict with the expected climate pattern in which monsoon precipitation is controlled by insolation. However, this discrepancy could be reconciled if evaporation loss determined by insolation and temperature was taken into consideration. We thus highlight the importance of local temperature (and evaporation loss) in controlling effective moisture in this arid/semi-arid region.

Acknowledgments

The authors would like to thank Dr. Hongxuan Lu (IEE, CAS), and groups from CUGB and Nanjing Institute of Geography and Limnology (CAS) for the help during the field work. We are also grateful to Prof. Zhisheng An, Dr. Xiangzhong Li and Dr. Zheng Wang for the useful discussion. Hong Yang and an anonymous reviewer are thanked for the constructive comments. The research was supported by the National Natural Science Foundation of China grants #41030211 (HD), #40873011 (WL), #91028005 (CLZ), and #41002123 (HJ); National Key Funds of China #2010CB833400 (WL); and KLSLRC (KLSLRC-KF-13-DX-2). Sample analysis was completed in the State Key Laboratory of Marine Geology through the "National Thousand Talents Program" at Tongji University (CLZ).

Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, http://dx.doi.org/10.1016/j.chemgeo.2014.01.009. These data include Google map of the most important areas described in this article.

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